Entropic stochastic resonance in a confined structure driven by dichotomous noise and white noises*

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The entropic stochastic resonance (ESR) in a confined system subjected to dichotomous noise and white noise and driven by a periodic sinusoidal force along the x axis of the structure and a time-dependent force in the declining direction, is investigated. Under the adiabatic approximation condition and based on the two-state theory, the expression of the output signal-to-noise ratio (SNR) is obtained. The results show that the SNR is a non-monotonic function of the strengths of dichotomous noise, white noise, and correlated strength of correlated noise. In addition, the SNR varies non-monotonically with the increase of the shape parameters of the confined structure, and also with the increase of the constant force along the y axis of the structure. The influence of the correlation rate of the dichotomous noise, and that of the frequency of the periodic force on the SNR are discussed.

Keywords: entropic stochastic resonance, dichotomous noise, correlated noise, square-wave signal, signal-to-noise ratio

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1. Introduction

Stochastic resonance (SR) began with the study of climatic dynamics by Benzi *et al.*[1] in 1981, when they invoked this phenomenon to explain the Earth's climatic change and the eccentricity of the Earth's orbit varying periodically in time. If the amplitude of this variation is too small to explain the succession of ice ages and relatively warm periods, the periodical phenomenon is amplified by some perturbations. This cooperative effect between the coherent 'signal' and the 'noise' was called stochastic resonance (SR). Researchers have investigated SR experimentally and theoretically.[1−11] The SR is considered as a cooperative result of the periodic signal and noise in a nonlinear system. In addition, the SR in a linear system driven by a colored multiplicative noise or a dichotomous noise was also observed.[2] These results have led to an extensive application of the SR in many scientific fields, such as electronic systems,[3] laser systems,[4] threshold systems,[5] biological systems,[6] and additive white Gaussian noise channel,[7] etc. The conventional SR is a nonlinear effect that accounts for the optimal response of a dynamical system to an external force at a certain noise intensity. The SR in a broad sense means the non-monotonic behaviour of the output signal as a function of some characteristics of the noise (noise intensity or noise correlation time) or of a periodic force (amplitude or frequency).

The diffusive behaviour of Brownian particles depends mainly on their size, the interaction between them, and the environment where they are situated. In addition to these characteristics, particles are confined within narrow, tortuous structures,[12−14] such as nanopores, zeolites, biological cells, and microfluidic devices, and the restriction on the space available for the particles will cause entropic barriers that will have a strong influence on the diffusive behaviour. In addition, geometrical confinements and entropic barriers also play a prominent role in the context of the SR phenomenon.[15−19] Burada *et al.*[16−18,20] presented a novel scheme for the appearance of the SR when the dynamics of a Brownian particle take place in a confined medium. The presence of uneven boundaries, giving rise to an entropic contribution to the poten-

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tial upon application of a periodic driving force, may result in an increase of the spectral amplification at an optimal value of the ambient noise level. This phenomenon is called entropic stochastic resonance (ESR). Zhao *et al.*[21] investigated the phenomenon of ESR in a two-dimensional confined system driven by a transverse periodic force when the coloured fluctuation was included in the system. Riefler *et al.*[22] investigated the transport of spherical Brown particles of finite size through narrow channels with varying cross-section width. The transient properties and SR of a Brownian particle moving in a confined system in the presence of an entropic barrier and subjected to a small periodic force and correlated noises, were studied.[23]

Dichotomous noise (DN) is widely studied in physical, chemical, biological, and other areas,[24,25] which can be generated by a two-state Poisson process. Because of its relatively simple calculation and well-defined limiting procedures leading to both Gaussian white noise and white shot noise, coloured dichotomous noise has received more and more attention. In an actual system, white noise and dichotomous noise may simultaneously exist. For example, a digital circuit may be perturbed by Gaussian white noise resulting from the background noise of the circuit; at the same time, it may be disturbed by random telephone noise (one form of dichotomous noise) induced by other digital circuits close to it. On the other hand, correlated noise has been widely used in various fields,[26−29] for example, in the statistical properties for bistable kinetics tumor cell growth and barrier crossing dynamics. Fulinski[30] studied the non-monotonic relaxation of a linear process under the influence of non-Markov DN. Broeck and Hanggi[31] calculated the escape rate for stochastic bistable flow driven by Markov DN. Neiman *et al.*[32] studied the synchronization of the noisy bistable system to a Markov DN. Based on the ordinary Langevin equation, Morita[33] investigated the dynamic behaviour of free Brownian motion of a particle driven by DN, and calculated the characteristic function for the Langevin equation. Balakrishnan *et al.*[34] calculated the mean first passage times of non-Markov DN of finite correlation time. Gitterman[24] studied an under-damped linear oscillator and found that the output signal of the oscillator with DN perturbation frequency shows non-monotonic dependence on the strength and the rate of the DN. Jin *et al.*[35] investigated the SR phenomenon in an over-damped linear system due to DN modulated by a bias signal, and found the occurrence of the conventional SR and the SR in a broad sense. The objective of the present work is to investigate the mobility of Brownian particles in channels. In particular, we are interested in both the non-monotonic influences of the dichotomous noise and correlated additive noises, and the influences of the square-wave signal and the parameters of the confined system on the output signal of the confined system.

The rest of the present paper is organized as follows. In Section 2, a model for Brown motion in a confined medium, driven by white noises as well as by dichotomous noise, is introduced. Under the adiabatic approximation condition, for the quartic double-well structure, the signal-to-noise ratio (SNR) is obtained. In Section 3, the ESR phenomenon in a confined system is presented. The influences of the geometrical shape and confinement on the output SNR are discussed.

2. Confined system and its output signal-to-noise ratio

The dynamics of a particle in a constrained geometry subjected to a sinusoidal oscillating force $F(t)$ along the x axis of the structure and to a time-dependent force $G(t)$ in the declining direction, depicted in Fig. 1, can be described by the Langevin equation written as

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = -\boldsymbol{G}(t) - F(t)\boldsymbol{e}_x + \boldsymbol{\eta}(t) + B_0\boldsymbol{\Gamma}(t), \qquad (1)$$

where $\boldsymbol{r} = (x, y)$ means the position of the particle; $\boldsymbol{e}_x$ is the unit vector along the x direction; $F(t) = A\cos(\Omega t)$, with A and Ω being the amplitude and angular frequency of the sinusoidal driving force, respectively; $\boldsymbol{G}(t)$ denotes a time-dependent force consisting of a constant force G along the y axis and a time modulated stochastic process, $G(t) = G[1+\boldsymbol{\xi}(t)]$, with $\boldsymbol{\xi}(t) = (\xi_x(t), \xi_y(t))$; $\boldsymbol{\eta}(t) = (\eta_x(t), \eta_y(t))$ corresponds to white noises with zero mean and variance

$$\begin{aligned} \langle \xi_i(t)\xi_j(t_1)\rangle &= 2D_\xi\delta_{ij}\delta(t-t_1), \\ \langle \eta_i(t)\eta_j(t_1)\rangle &= 2D_\eta\delta_{ij}\delta(t-t_1), \qquad (2) \\ \langle \xi_i(t_1)\eta_j(t_2)\rangle &= \langle \eta_i(t_1)\xi_j(t_2)\rangle \\ &= 2c\sqrt{D_\eta D_\xi}\delta_{ij}\delta(t_1-t_2), \qquad (3) \end{aligned}$$

for $i, j = x, y$, respectively, with c being the coupled strength between noise $\boldsymbol{\xi}(t)$ and $\boldsymbol{\eta}(t)$; $\boldsymbol{\Gamma}(t)$ is a dichotomous noise, with unit amplitude $\Gamma_\pm = \pm 1$ and transition rate λ. The white noise $\boldsymbol{\eta}(t)$ is the thermal

noise of the system, responsible for stochastic switching between metastable states. The dichotomous noise $\boldsymbol{\Gamma}(t)$ denotes an external stochastic force, correlated to neither $\boldsymbol{\xi}(t)$ nor $\boldsymbol{\eta}(t)$, which can influence the switching events between states of the system. We assume that the magnitude B_0 of the dichotomous noise is small enough so that it cannot induce any transition between metastable states of the system by itself. It was shown that the addition of dichotomous noise leads to dramatic changes in a bistable system.[32,36] In particular, dichotomous noise can synchronize the switching events, resulting in the mean switching rate of the system being locked and equal to the flipping rate of dichotomous noise in a finite range of thermal noise intensity.

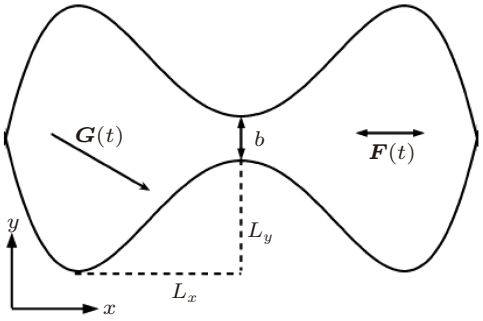


Fig. 1. Schematic diagram of the two-dimensional structure, a Brownian particle moves in the confined medium, driven both by a sinusoidal oscillating force $F(t)$ along the x axis of the structure and by a time-dependent force $G(t)$ in the declining direction.

Using the Novikov theorem and Fox's approach,[23,37–41] it follows from Eqs. (2) and (3) that equation (1) can be equivalently transformed into the following stochastic differential equation:

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = -G\boldsymbol{e}_y - F(t)\boldsymbol{e}_x + \sqrt{D_{\varsigma 0}}\boldsymbol{\varsigma}(t) + B_0\boldsymbol{\Gamma}(t), \quad (4)$$

where $\boldsymbol{\varsigma}(t)$ denotes a Gaussian white noise with zero mean and correlation $\langle \varsigma(t_1)\varsigma(t_2)\rangle = 2\delta_{ij}\delta(t_1 - t_2)$, for $i, j = x, y$, and $D_{\varsigma 0} = D_\xi G^2 - 2c\sqrt{D_\xi D_\eta}G + D_\eta$.

For the structure depicted in Fig. 1, the walls are defined by

$$w_{\mathrm{l}}(x) = L_y(x/L_x)^4 - 2L_y(x/L_x)^2 - \frac{b}{2} = -w_{\mathrm{u}}(x), \quad (5)$$

where w_{l} and w_{u} correspond to the lower and the upper boundary functions, respectively, L_x denotes the distance between the bottleneck position and position of maximal width, L_y refers to the narrowing of the boundary functions, and b to the remaining width at the bottleneck, $2w(x) = w_{\mathrm{u}}(x) - w_{\mathrm{l}}(x)$ gives the local width of the structure. For the sake of a dimensionless description, we scale all lengths by the characteristic length L_x, i.e., $\tilde{x} = x/L_x$, $\tilde{y} = y/L_x$, $\tilde{b} = b/L_x$, and $\tilde{w}_{\mathrm{l}} = w_{\mathrm{l}}/L_x = -\tilde{w}_{\mathrm{u}}$. Supposing an irrelevant reference temperature T_{R} and time in the units of $\tau = L_x^2/k_{\mathrm{B}}T_{\mathrm{R}}$ (here k_{B} is the Boltzmann constant) then the particle takes twice the time to diffuse a distance L_x at temperature T_{R}, i.e., $\tilde{t} = t/\tau$ and $\tilde{\Omega} = \Omega\tau$. We scale forces by $F_{\mathrm{R}} = L_x/\tau$, so the orthogonal force $\tilde{G} = G/F_{\mathrm{R}}$ and the sinusoidal force $\tilde{F}(\tilde{t}) = F(t)/F_{\mathrm{R}}$. In the following we omit the tilde symbols for better legibility. In dimensionless form the Langevin equation (1) and the boundary function (5) read

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = -G\boldsymbol{e}_y - F(t)\boldsymbol{e}_x + \sqrt{D_\varsigma}\boldsymbol{\varsigma}(t) + B\boldsymbol{\Gamma}(t), \quad (6)$$

$$w_{\mathrm{l}}(x) = -w_{\mathrm{u}}(x) = \varepsilon x^4 - 2\varepsilon x^2 - b/2, \quad (7)$$

where we have defined the aspect ratio $\varepsilon = L_y/L_x$ and the dimensionless temperature $D_\varsigma = D_{\varsigma 0}/(k_{\mathrm{B}}T_{\mathrm{R}})$ and dichotomous noise amplitude $B = B_0/T_{\mathrm{R}}$. By virtue of the symmetry of the structure, i.e., $w_{\mathrm{u}}(x) = -w_{\mathrm{l}}(x)$ and the definition of the half width function $w(x) = (w_{\mathrm{u}} - w_{\mathrm{l}})/2$, the potential function becomes [17,42]

$$U(x) = -D_\varsigma \ln\Big[\frac{2D_\varsigma}{G}\sinh\Big(\frac{Gw(x)}{D_\varsigma}\Big)\Big]. \quad (8)$$

The master equation of the system can be described as[24,38]

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\rho(x,\Gamma) = &- W_0(x_+,\Gamma_+)\rho(x_+,\Gamma_+) \\ &+ W_0(x_-,\Gamma_+)\rho(x_-,\Gamma_+) \\ &+ \lambda[\rho(x_+,\Gamma_-) - \rho(x_+,\Gamma_+)]. \end{aligned} \quad (9)$$

Here $x_\pm = \pm 1$ indicate the positions of the minimum of the symmetric potential $U(x)$, $\Delta U = U(x_\pm) - U(0)$ is the barrier of the bistable potential

$$W_0(x_\pm,\Gamma_\pm) = \exp\Big(-\frac{\Delta U + x_\pm\Gamma_\pm B}{D_\varsigma}\Big) \quad (10)$$

and the mean switching frequency of the output $x(t)$ is given by[24,38]

$$\langle W\rangle_{\mathrm{out}} = \frac{\pi}{2}\Big[a_1 + a_2 - \frac{(a_2 - a_1)^2}{a_1 + a_2 + 2\lambda}\Big] \quad (11)$$

with the rates

$$a_{1,2} = \exp\big[-(\Delta U \pm B)/D_\varsigma\big]. \quad (12)$$

For the case of a sufficiently slow and weak harmonic force $F(t)$, one can obtain the modification rate as[24,38]

$$W(x,\Gamma) = W_0(x,\Gamma)\exp[-A\Gamma\cos(\Omega t)/D_\varsigma]. \quad (13)$$

From master equation (9) with the modification rate (Eq. (13)), the autocorrelation function can be obtained as

$$\begin{aligned}&\frac{\mathrm{d}}{\mathrm{d}t}\langle x(t)x(t_1)\rangle\\&=-(a_1+a_2)\langle x(t)x(t_1)\rangle+(a_2-a_1)\langle \Gamma(t)x(t_1)\rangle\\&\quad+[(a_1+a_2)\langle x(t_1)\rangle-(a_2-a_1)\langle x(t)\Gamma(t)x(t_1)\rangle]\\&\quad\times A\cos(\Omega t)/D_\varsigma. \end{aligned}\tag{14}$$

The equation for the cross-correlation function reads

$$\frac{\mathrm{d}}{\mathrm{d}t}\langle \Gamma(t_1)x(t_2)\rangle=-2\lambda\langle \Gamma(t_1)x(t_2)\rangle. \tag{15}$$

After the Fourier transform, one obtains the power spectrum as

$$S(\omega)=N(\omega)+A^2\pi M\delta(\omega-\Omega). \tag{16}$$

Here, $N(\omega)$ is the power spectrum of the background

$$\begin{aligned}N(\omega)=&-\frac{a_1+a_2}{(a_1+a_2)^2+\omega^2}\Big[1+\frac{(a_2-a_1)^2}{4\lambda^2+\omega^2}\Big]\\&-\frac{4(a_2-a_1)^2}{(a_1+a_2+2\lambda)(4\lambda^2+\omega^2)},\end{aligned}\tag{17}$$

and M is the spectral power amplification

$$M=\frac{4}{\pi^2D_\varsigma^2}\frac{\langle W\rangle_{\mathrm{out}}^2}{(a_1+a_2)^2+\Omega^2}. \tag{18}$$

The SNR is defined as

$$\mathrm{SNR}=\frac{\pi M}{N(\Omega)}. \tag{19}$$

3. Discussion and conclusion

Constrained motion impeding the access of a Brownian particle into certain regions of space can be described in terms of a bistable entropic potential. The activated dynamics of the particle in this effective potential can lead to a cooperative effect between noise and external modulation, yielding an ESR phenomenon. In the present work, we consider a confined structure with dichotomous noise and white noises. The influences of the noises and the parameters of the confined structure on the system SNR are analysed from Figs. 2–7. The SNR versus the amplitude B of the dichotomous noise is plotted in Fig. 2. One can clearly see that for certain values of B the SNR can be maximized; therefore appropriate amplitude of the dichotomous noise has a positive effect on the system output. This nonlinear dependence of the SNR on the dichotomous noise amplitude is a new result, which was not studied in Refs. [24]–[28], [40] and [42]. Moreover, from Fig. 2, one can conclude that the SNR is also a non-monotonic function of coupled strength c. For small values of B ($0 < B < 0.12$), the SNR decreases with the increase of coupled strength c; while for large values of B ($0.12 < B < 0.5$), the SNR increases with the decrease of c. The peaks of the SNR curves shift toward larger magnitude B of the dichotomous noise for large values of c, which suggests that with the increase of B, one must enhance coupled strength c between the white noises for the SNR to reach its maximal value.

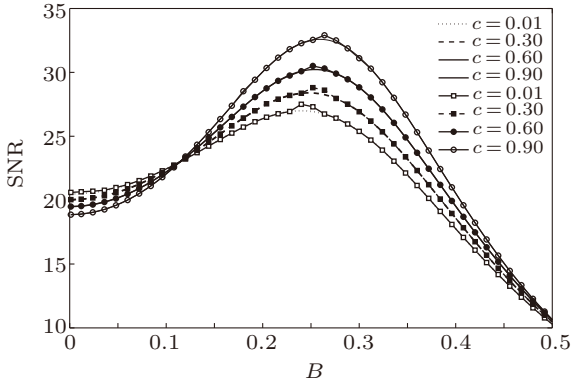


Fig. 2. Curves of signal-to-noise ratio (SNR), obtained from Eqs. (17)–(19) versus amplitude B of the dichotomous noise. Thin solid line corresponds to the SNR for coupled strength $c = 0.01$ between the white noises;, thick solid line, dash–dot line, and dotted line correspond to the SNRs for $c = 0.3$, 0.6, 0.9, respectively. Other parameters are $G = 0.1$, $\varepsilon = 0.1$, $b = 0.1$, $D_\xi = 0.2$, $D_\eta = 0.08$, $\Omega = 0.06$, and $\lambda = 0.9$. The lines with no markers refer to the analytical results from Eqs. (17)–(19), and the lines with markers represent numerical simulation results.

Figures 3 and 4 show the curves of SNR versus noise intensities D_η and D_ξ of the white noises $\eta(t)$ and $\xi(t)$ for different values of the coupling strength c, respectively. It can be seen that there is a peak on each of the SNR curves for certain values of the noise strengths, which characterizes the ESR phenomenon in the confined structure. The enhancement of ESR can be explained using the mean switching frequency (MSF) from potential well.[43] For small noise intensity, the MSF approaches to slow dichotomous noise $\lambda \to 0$. For intermediate values of noise intensities D_η and D_ξ the MSF is locked and changes very slowly with the increase of noise strength. The small noise intensity region represents a potential with a lowered barrier, so that the ESR may occur. This is why ESR is greatly improved. In addition, from the two figures,

one can see that with the increase of correlation rate λ of the dichotomous noise, the SNR increases monotonically. Thus the correlation rate can enhance the system output signal.

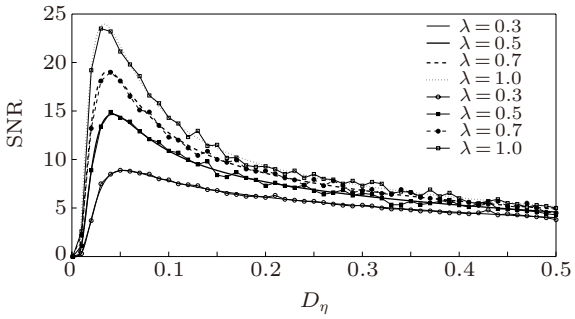


Fig. 3. Curves of signal-to-noise ratio (SNR) obtained from Eqs. (17)–(19) versus strength D_η of Gaussian noise $\boldsymbol{\eta}(t)$. Thin solid line corresponds to the SNR for correlation rate $\lambda = 0.3$ of the dichotomous noise; thick solid line, dashed line, and dotted line correspond to the SNRs for $\lambda = 0.5$, 0.7, 1.0, respectively. Other parameters are $G = 0.1$, $\varepsilon = 0.2$, $b = 0.2$, $B = 0.4$, $\Omega = 0.1$, $c = 0.4$, and $D_\xi = 0.1$. The lines with no markers refer to the analytical results from Eqs. (17)–(19), and the lines with markers represent numerical simulation results.

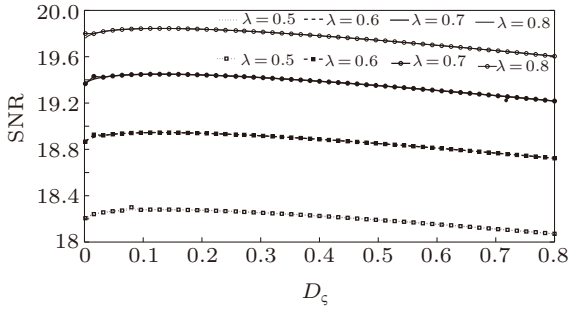


Fig. 4. Curves of signal-to-noise ratio (SNR) obtained from Eqs. (17)–(19) versus strength D_ξ of Gaussian noise $\boldsymbol{\xi}(t)$. Thin solid line corresponds to the SNR for the correlation rate $\lambda = 0.5$ of the dichotomous noise; thick solid line, dashed line, and dotted line correspond to the SNRs for $\lambda = 0.6$, 0.7, 0.8, respectively. Other parameters are $G = 0.1$, $\varepsilon = 0.25$, $b = 0.2$, $B = 0.3$, $\Omega = 0.001$, $c = 0.08$, and $D_\eta = 0.2$. The lines with no markers refer to the analytical results from Eqs. (17)–(19), and the lines with markers represent numerical simulation results.

Figure 5 shows the curves of SNR versus force G for different values of correlation rate λ. For some intermediate values of G, the SNR reaches its maximal value, indicating the characteristic of the entropic parameter-induced resonance phenomenon. This phenomenon is investigated in the presence of a purely energetic barrier,[44] which means that by tuning system parameters of the confined structure, the resonance-like behaviour can be obtained.

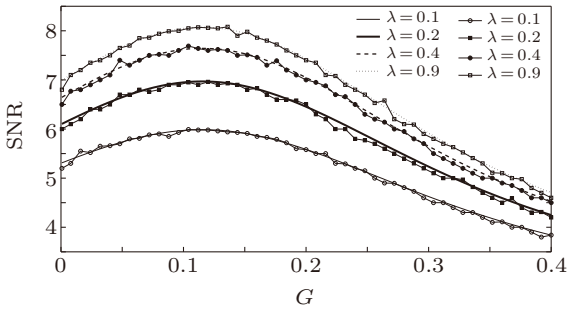


Fig. 5. Curves of signal-to-noise ratio (SNR) obtained from Eqs. (17)–(19) versus force G. Thin solid line corresponds to the SNR for the correlation rate $\lambda = 0.1$ of the dichotomous noise; thick solid line, dashed line, and dotted line correspond to the SNRs for $\lambda = 0.2$, 0.4, 0.9, respectively. Other parameters are $\varepsilon = 0.15$, $b = 0.02$, $B = 0.1$, $\Omega = 0.1$, $D_\xi = 0.12$, $c = 0.4$, and $D_\eta = 0.01$. The lines with no markers refer to the analytical results from Eqs. (17)–(19), and the lines with markers represent numerical simulation results.

The dependences of SNR on the remaining width b at the bottleneck and on system parameter ε of the confined structure are analysed from Figs. 6 and 7, respectively. From the two figures, one can easily observe the resonance behaviour of the SNR versus the parameters of the confined structure, i.e., the ESR phenomenon occurs. Therefore, the SNR depends non-monotonically on the shape of the region, i.e., the width b and the system parameter ε. By adjusting its characteristic geometric parameters one may optimize the system response. Furthermore, from Fig. 6, one can find that with the decrease of frequency Ω of the periodic force, the magnitude of the peak increases, and its position shifts toward large values of the remaining width b, which suggests that for low frequency Ω, a wider width b should be selected for the SNR to obtain its maximum value.

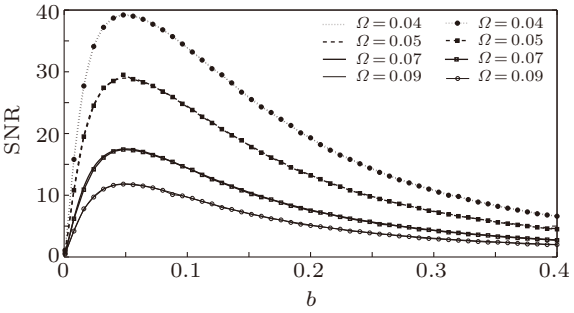


Fig. 6. Curves of signal-to-noise ratio (SNR) obtained from Eqs. (17)–(19) versus width b at the bottleneck of the confined structure. Thin dotted line corresponds to the SNR for the frequency $\Omega = 0.04$ of the periodic force $F(t)$; dash–dot line, thick solid line, and thin solid line correspond to the SNRs for $\Omega = 0.05$, 0.07, 0.09, respectively. Other parameters are $G = 0.2$, $\varepsilon = 0.05$, $B = 0.1$, $\lambda = 0.5$, $D_\xi = 0.12$, $c = 0.2$, and $D_\eta = 0.1$. The lines with no markers refer to the analytical results from Eqs. (17)–(19), and the lines with markers represent numerical simulation results.

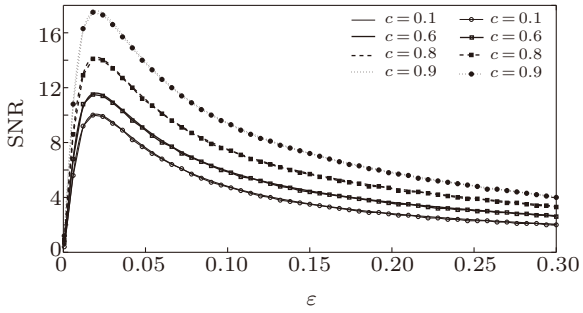


Fig. 7. Curves of signal-to-noise ratio (SNR) obtained from Eqs. (17)–(19) versus parameter ε of the confined structure. Thin solid line corresponds to the SNR for the coupled strength $c = 0.1$ between the white noises; thick solid line, dashed line, and dotted line correspond to the SNRs for $c = 0.6$, 0.8, 0.9, respectively. Other parameters are $G = 0.5$, $b = 0.02$, $B = 0.1$, $\Omega = 0.1$, $\lambda = 1$, $D_\xi = 0.12$, and $D_\eta = 0.01$. The lines with no markers refer to the analytical results from Eqs. (17)–(19), and the lines with markers represent numerical simulation results.

4. Conclusion

In this paper we investigated ESR in the confined structure in the presence of dichotomous noise and white noises and driven both by a sinusoidal oscillating force along the x axis of the structure and by a time-dependent force in the declining direction. By using the Novikov theorem and Fox's approach, and for the case of a sufficiently slow and weak harmonic force, the expression of the system SNR is obtained. Three kinds of resonance behaviours are observed: the SNR as a function of the parameters of the noises, i.e., the intensities of the white noises and the strength between these noises, and the amplitude of the dichotomous noise; secondly, the SNR as a function of external force, i.e., force G; finally, the SNR as a function of the shape of the confined structure. It is shown that the ESR phenomenon can occur in a confined structure with white noises.[35] In the present work, in the presence of additive dichotomous noise, we find that the system SNR also shows ESR behaviour as a function of the dichotomous noise, which was not studied in Ref. [35]. It is believed that the results obtained in this paper can be of certain help for further investigations of the ESR phenomenon in a confined structure subjected to dichotomous noise and correlated white noises, and also for the optimization and control inside a corrugated structure, where proper choice of external force and the structure parameter can optimize the output signal.

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